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Analysis of Superimposed Elementary Thermodynamic Cycles: from the Brayton-Joule to Advanced Mixed (Auto-Combined) Cycles*

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Abstract

The need for efficiency improvement in energy conversion systems leads to a stricter functional integration among system components. This results in structures of increasing complexity, the high performance of which are often difficult to be understood easily. To make the comprehension of these structures easier, a new approach is followed in this paper, consisting in their representation as partial or total superimposition of elementary thermodynamic cycles. Although system performance cannot, in general, be evaluated as the sum of the performance of the separate thermodynamic cycles, this kind of representation and analysis can be of great help in understanding directions of development followed in the literature for the construction of advanced energy systems, and could suggest new potential directions of work. The evolution from the simple Brayton-Joule cycle to the so called “mixed” cycles, in which heat at the turbine discharge is exploited using internal heat sinks only without using a separate bottoming section, is used to demonstrate the potentiality of the approach. Mixed cycles are named here "auto-combined cycles” to highlight the combination of different (gas and steam) cycles within the same system components.

Keywords: *Superimposition, elementary thermodynamic cycles, Brayton, Auto-combined cycle.*

1. Introduction

The construction of new energy system structures (synthesis problem) may require efficient criteria to be used in order to exploit the benefits, in terms of performance/efficiency, deriving from the functional interactions among components. New structures are usually proposed in the literature as improvements of previous ones following a heuristic approach in which the experience of the designer plays a fundamental role. Most of the developments are based on the search for a better heat transfer interaction among system components, which consists in searching for heat sinks, or in adding new sinks and sources. This procedure may require the addition of new working fluids and, in turn, of new elementary thermodynamic cycles that are to be matched properly with the initial one to improve system performance/efficiency.

Having this in mind, it was suggested (Lazzaretto and Segato, 1999, 2001; Lazzaretto and Toffolo, 2006, 2008) that the key to interpret complex system configurations consists of creating the so called “basic plant configuration” **i)** in which thermal links among components different from the heat exchangers are cut (i.e. the temperature at the outlet of a component is considered as independent from the temperature at the inlet of the component that follows), so that only thermal flows that may be heated or cooled appear in the system structure instead of the heat exchangers. These thermal flows are included in a black-box which may release heat to the environment (a similar approach was used by De Ruyck et al. (1997) where, however, the black-box is considered as adiabatic).

Moreover, in Lazzaretto and Toffolo (2006; 2008) **ii)** it was proposed to “read” the overall system structure as superimposition of “elementary sequences” dictated by the “elementary cycles”. The optimization of the design parameters of a given system structure, built according to the criterion given at point **i)**, was performed in Lazzaretto and Toffolo (2006; 2008).

The focus in this paper is instead on point **ii)**, i.e. on the advantages, in terms of comprehension of the system behavior, in representing the system configuration as superimposition of elementary thermodynamic cycles. To this end, the evolution of the simple Brayton-Joule cycle (called Brayton in following sections for simplicity) towards more advanced configurations of mixed (auto-combined) cycles (Dellenback, 2002; Abdallah and Harvey, 1997; Korobitsyn, 1998; Macchi et al., 1995; Chiesa et al., 1995; Nelson et al., 2002; Horlock, 2003; Rice, 1995; Frutschi and Plancherel, 1988; Chodkiewicz et al., 2001; Gambini and Guizzi, 1997; Xu et al., 2006; Jericha et al., 2003; Sanz et al., 2004; Aoki et al., 1998; Desideri et al., 2001; Bannister et al., 1999; Gambini et al., 2003) is analyzed.

2. Heat Recovery from the Brayton-Joule Cycle

2.1 On the Need of Heat Sinks

The heat flow at high temperature released by the Brayton cycle at the turbine outlet is a thermal source that has to be exploited with the maximum efficiency when the Brayton cycle is the core of a more complex energy system. The design challenge consists in searching for suitable heat sinks within the system, which allow the temperature of the heat stream at the turbine outlet to be reduced before this stream is rejected to the ambient. The air preheating at the compressor outlet, typical of regenerative cycles, allows for a partial use of the heat discharged by the turbine, being the compressed air already at high temperature. Margins for improvement derive from the intercooling of the compressed air, which reduces the temperature at the compressor outlet as well. In regenerative cycles proposed recently (Dellenback, 2002), the regenerator is followed by

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an additional turbine stage to lower the exhaust gas temperature, which, however, is still far from the ambient value.

It appears therefore that it is necessary to include heat sinks in the system structure at low temperature and/or to substitute the compressed air with a different heat sink.

2.2 Chemical and Thermal Ways for Heat Recovery

Two main criteria can be used for heat recovery from the gases exiting the turbine:

1) Chemical recovery, which consists in increasing the energy content of the system fuel using a reforming reaction. This is done in the Chemically Recuperated Gas-Turbines (CRGT) (Abdallah and Harvey, 1997; Korobitsyn, 1998), in which the high temperature stream at the turbine outlet is used for a partial or total natural gas reforming. Reforming still occurs in a temperature range similar to or higher than that of the regenerator, so that heat recovery cannot be complete and is to be integrated with other heat sinks at lower temperature.
2) The "normal" way for thermal recovery consists instead in using water as heat sink in order to generate superheated steam for a bottoming cycle. The resulting system configuration is a "combined cycle". A two or three pressure level heat recovery steam generator reduces the irreversibilities in the gas-steam heat transfer reducing the flue gas temperature at the same time.

3. STIG Cycle and its Evolution

Recently, considerable amount of efforts were devoted in the literature to the development of "Mixed cycles", mainly based on the STIG cycle (see, e.g., Macchi et al., 1995; Chiesa et al., 1995). The basic idea is to still use water as heat sink, while maintaining at the same time a simpler plant configuration than the combined cycle. The basic STIG plant configuration is shown in Figure 1. As explained in Section 1, this configuration does not include heat exchangers but hot or cold thermal flows only (heat transfer is represented by an arrow).

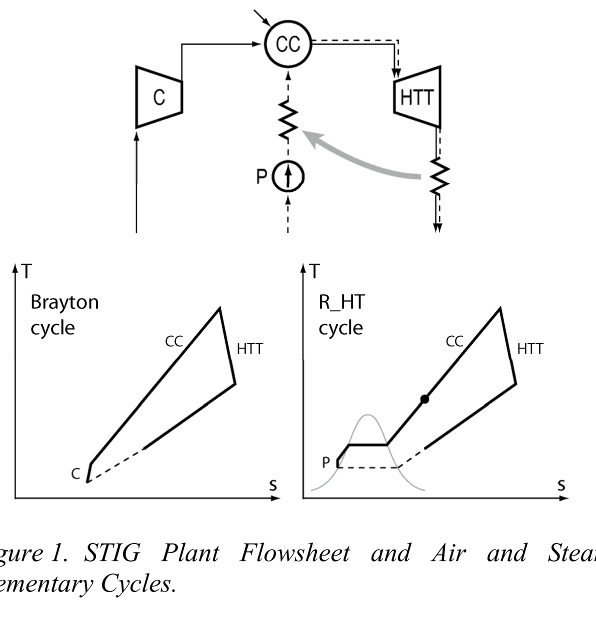

Figure 1. STIG Plant Flowsheet and Air and Steam Elementary Cycles.

The flue gas heat at the turbine outlet is used to generate steam which is sent to the combustion chamber and then expanded in the turbine. The new system configuration can be seen as a partial superimposition of the two thermodynamic cycles having air and water/steam as working fluids, the latter being "sustained" (i.e. receiving heat) by the former (see, also Nelson et al., 2002). In this sense this cycle is called here (and those that will be derived from it) "*auto-combined cycle*" instead of "*mixed cycle*". The thermodynamic cycles of the air and water/steam streams are shown separately in Figure 1.

The working fluid in the Brayton cycle is air and combustion products, whereas in the Rankine cycle it is water/steam only. The two elementary cycles operate with the same maximum temperature of the mixture and within the same pressure ranges. Although the thermodynamic transformations of the separate working fluids are different from those of the mixture (and the superimposition of the effects does not hold strictly when real properties of the substances are considered), this representation is proposed to find indications about the convenience, measured in terms of efficiency improvement, of increasing/decreasing the percentage of each component of the mixture.

Steam flows through a Rankine cycle with superheating at high temperature (denoted as R_HT in following sections). In this cycle, heat is supplied in two phases:

- in the HRSG through a heat recovery;
- in the combustion chamber through fuel firing.

In a theoretical way, the thermal efficiency of this R_HT cycle can be evaluated as the ratio between the net work and the heat supplied in two phases. This can be done by "artificially" neglecting the thermal link between the Brayton cycle and the R_HT and assuming that the latter may exist autonomously by an external heat supply. Note that, compared to a traditional superheated Rankine cycle, the R_HT cycle shows a much higher superheating temperature and consequently a much higher temperature at the turbine outlet. This feature makes it suitable to be used as a topping cycle. However, it appears that the thermal efficiency of the R_HT cycle is about 10 to 15 points lower than the Brayton cycle at current technological limits for the turbine inlet temperature (1300-1400°C) and pressure ratio (30-40). Thus, it would not be convenient to substitute the Brayton cycle with an R_HT cycle as a topping cycle. In any case this would not be possible using the existing technology for external combustion due to temperature limits in the high temperature heat exchanger (Aquaro and Pieve, 2007; Kautz and Hansen, 2007).

In traditional gas turbine engines the stoichiometric air is approximately one third of the air at the compressor inlet since part of the air is used as a "thermal diluent" of the combustion to lower the combustion temperature to a desired value at the turbine inlet (TI). In a new design of a STIG power plant the compressor should be undersized compared to the turbine considering the same fuel flow rate to the combustion chamber of a reference gas turbine plant since the steam generated in the HRSG would partially substitute for air as the thermal diluent (one mass unit of steam would approximately replace two air mass units since the steam specific heat is about twice the specific heat of air). In summary, the working fluid in a STIG plant is made up of the following components:

- stoichiometric air that will be transformed (after combustion) into products of the stoichiometric combustion (denoted as A in the following sections),
- air used as the thermal diluent of combustion process (B),
- steam used as the thermal diluent of combustion process (C).

Components B and C are inactive in the combustion process: i.e., their role is solely to remove the excess heat generated. They necessarily have to be mixed with the stoichiometric air. So, they have to follow the same thermodynamic transformations of the stoichiometric air. Accordingly, the R_HT cycle cannot have an "autonomous life" in the heat supply phase to the cycle at high temperature.

3.1 Addition of a High Pressure Turbine to the STIG Cycle

The only way to improve the R_HT cycle is by acting on the heat supply phase at low temperature (before the combustion chamber inlet) where the cycle is "independent" of the Brayton cycle and heat can be supplied through a heat exchanger. The assumption here is to obtain this improvement using only the available thermal source of the flue gases at the turbine outlet. Studies performed in the literature aimed at maximizing system efficiency have demonstrated that there is an optimal amount of steam generated by thermal recovery which corresponds to the highest temperature at the combustion chamber inlet for a given approach temperature difference between flue gases and superheated steam (Horlock, 2003). Increasing the steam pressure would also be convenient, but this has a limit in the pressure of the Brayton cycle combustion chamber. To overcome this limit it was suggested (Rice, 1995) to add a high pressure turbine (see Figure 2) which expands steam down to the maximum Brayton cycle pressure. So, additional mechanical work is obtained at the expense of a lower temperature at the combustion chamber inlet.

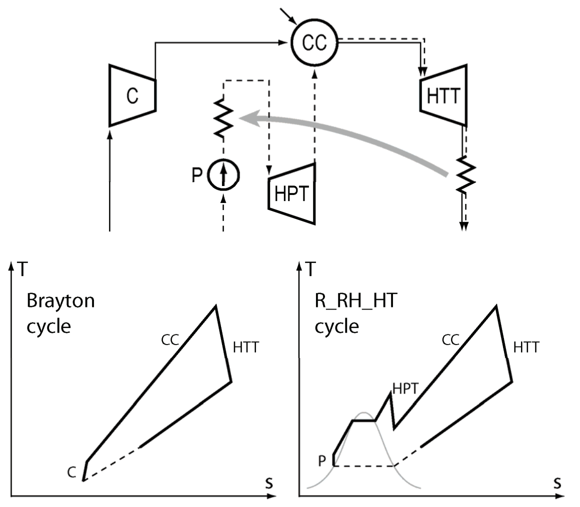

Figure 2. Addition of a High Pressure Turbine to the STIG Cycle.

Again, in a theoretical way it is possible to define a thermal efficiency for this elementary Rankine cycle with superheating and re-heating at high temperature (R_RH_HT), as already done for the R_HT cycle. An addendum appears at the numerator (the expansion work of the high pressure turbine) and two other terms are modified: the heat to be supplied at the denominator and the increased pump work at the numerator. The balance of the modification is such that the thermal efficiency of the R_RH_HT is higher than that of the R_HT cycle but still remains approximately 5 points lower than the Brayton cycle efficiency (in the same temperature and pressure ranges, and avoiding supercritical pressures). This results in an increase of the STIG cycle efficiency, while the efficiency of the elementary Brayton cycle is unaltered.

3.2 Advanced Mixed ("Auto-Combined") Cycles: Addition of High and Low Pressure Turbines to the STIG Cycle

Auto-combined cycles present the following limit in comparison with traditional combined cycles. The latter shows a thermodynamic loss associated with the flue gases exiting the turbine at approximately 120-140°C in a single pressure level plant or at about 80-90°C in a three pressure level plant. On the other hand, the value of the irreversibility loss associated with the heat released to the ambient in the condenser of the bottoming cycle is relatively low since the temperature of the steam in the condenser is quite close to the ambient temperature. In a STIG cycle steam is released to the ambient at about 120°C usually generated at a single pressure level. In evolved plant configurations (see Figure 3), steam is generated at two pressure levels (Frutschi and Plancherel, 1988): the high pressure steam is first expanded in the high pressure turbine, whereas the low pressure steam is directly sent to the combustion chamber.

Despite the additional complexity of the plant structure, the temperature of the steam rejected to the environment still remains higher than the temperature corresponding to vacuum condensation in the bottoming steam cycle of a combined plant. To overcome this limitation and make the efficiency of the auto-combined cycles closer to the combined cycle, a low pressure turbine (LPT) could also be included (see Figure 4), in which the cooled gas at the HRSG outlet is expanded.

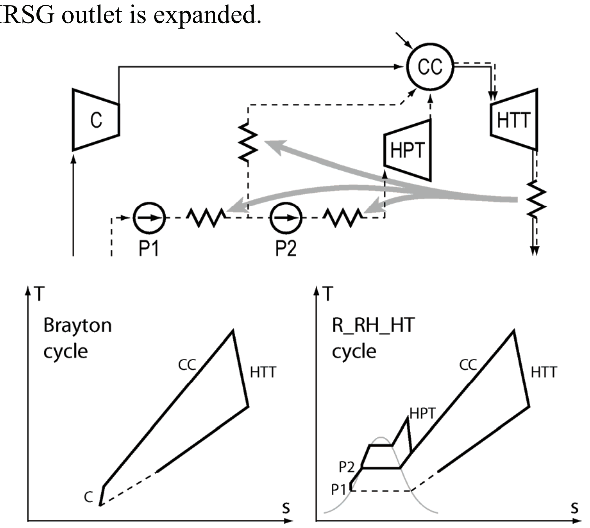

Figure 3. Two Pressure Level STIG Cycle with High Pressure Turbine.

Still, the expansion cannot reach the low vacuum pressure of a bottoming cycle, the condensing pressure being increased by the presence of air in the mixture. We have not found such a LPT in the literature in advanced air-based mixed cycles (as, instead, it appears in some power cycles with oxygen combustion, see Sections 4 and 5). The only similar option is the direct expansion without intercooling below the atmospheric pressure (see Chodkiewicz et al., 2001).

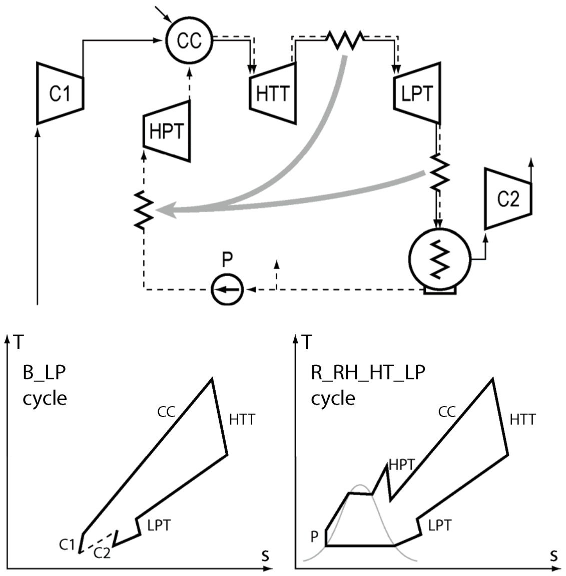

Figure 4. Addition of a High Pressure Turbine and Low Pressure Turbine to the STIG Cycle.

The addition of the low pressure turbine further modifies the elementary Rankine cycle, now called R_RH_HT_LP, which shows a higher efficiency than the previous one (R_RH_HT in Figure 3). In fact, the heat supplied is the same whereas the work obtained increases due to the contribution of the low pressure turbine. This modification also implies a modification of the elementary Brayton cycle (now named B_LP), which includes the further expansion after the gas cooling in the HRSG, down to a pressure lower than the atmospheric one. Condensation occurs at variable temperature depending on the steam partial pressure in the mixture which decreases as steam condenses. The temperature of the flows at the condenser outlet (water, air and combustion products) and the fraction of steam condensed depend on the thermodynamic conditions of the fluid used to remove the condensation heat. Water is then pumped at an almost negligible expense of work and sent to the HRSG in order to close the thermodynamic cycle (water generated in the combustion after condensation is rejected to the environment to fulfill the mass balance). As far as gas is concerned, an additional compressor (C2) is to be included to increase the pressure from the value at the condenser outlet to the ambient pressure, forming an open cycle. The compressor partially reduces the additional work obtained by gas expansion in the LPT, so that the B_LP cycle efficiency is only slightly higher than that of the Brayton cycle. The elementary Rankine cycle R_RH_HT_LP (Figure 4) features:

- Three expansions at high, medium and low pressures;
- Two heat acquisition phases, the first at high temperature in the combustion chamber, in which steam plays the role of thermal diluent (see Section 3), and the second at lower temperature in the HRSG;
- A heat release phase in the HRSG;
- A heat release phase in the condenser.

Assuming again that the entire heat is supplied by external heat sources, the thermal efficiency of the elementary R_RH_HT_LP steam cycle appears to be very close to that of the elementary Brayton cycle. Both of them can be considered as topping cycles since they make a large amount of heat available for recovery. An important difference exists, however, between the two elementary cycles: in contrast to the Brayton cycle which requires heat at high temperature only, a large amount of heat is required in the R_RH_HT_LP cycle at a lower temperature level (<600°C). At this temperature, heat can be transferred using heat exchangers, and this makes it possible to use less valuable fuels than natural gas in addition to heat recovery from internal heat sources, leaving natural gas for the high temperature heat transfer in the combustion chamber only, as suggested in the GIST cycle (Gambini and Guizzi, 1997). This, in turn, results in a higher steam content in the working fluid. This feature is also used in the partial gasification power plant suggested by Xu et al. (2006) where the heat supply is partially external and partially internal. The external part at low temperatures uses char as fuel and generates steam that is injected in the combustion chamber of a Brayton cycle, whereas the internal part is performed using clean syngas that is burnt directly in the same combustion chamber generating high temperature gases.

In general, high pressure steam is generated from heat recovery at the turbine outlet only. Nevertheless, if the thermal efficiency of the elementary steam cycle were higher than that of the elementary Brayton cycle, it would be meaningful to increase the amount of steam injected in the combustion chamber (see, e.g., the H_2/O_2 cycles discussed in Section 5) in order to have steam as thermal diluent generated by only thermal recovery.

The discussion here focuses on the elementary Rankine cycle. However, margins for improvements exist also for the efficiency of the elementary Brayton cycle, mainly deriving from an inter-cooled compression, which decreases the work absorbed in the compression itself.

The advantage of these solutions is in any case to be verified from the economic point of view.

4. Auto-combined Cycles Based on Oxy-combustion and CO_2 Capture (GRAZ and S-GRAZ)

CO_2 capture is one of the most challenging issues facing energy conversion systems. The simplest method for existing plant consists of chemical CO_2 separation by solution of ethanolamines. A drawback of this method is the high amount of heat required for ethanolamines regeneration. Two other options are fuel decarbonization and oxy fuel combustion, which both imply a specific plant design. In particular, the combustion products of the oxy-fuel combustion are made up of CO_2 and steam, from which steam can be easily separated through condensation (see Figure 5). CO_2 is captured whereas steam is rejected to the environment. The elementary oxy-fuel combustion plant configuration is a gas turbine engine connected to an Air Separation Unit (ASU), the high power consumption of the latter being the main drawback of the system. In order to maintain the number of chemical species in the working fluid equal to two, CO_2 is used as thermal diluent of combustion (this CO_2 operates in a closed Brayton cycle).

The following discussion about the evolution of the simple oxy-fuel cycle towards more complex system structures mainly focuses on:

- the presence in the system structure and the features of the Brayton cycle operating with the combustion thermal diluents,
- the internal heat recovery for steam generation in "auto-combined" cycles, such as in those shown in Section 3.

The heat of the gases exiting the turbine can be used in a bottoming steam cycle as happens in traditional combined cycles or can be used to generate steam to be injected in the combustion chamber as described in Section 3 for the STIG cycle. In this case, steam plays the role of thermal diluent of the combustion substituting a part of the CO_2. The working fluid is therefore made up of the three following components:

- the stoichiometric oxygen and the products of the stoichiometric combustion (steam and CO_2) (denoted as A in following sections);
- the CO_2 thermal diluent of the combustion (B);
- the steam thermal diluent of the combustion, generated through heat recovery and injected in the combustion chamber (C).

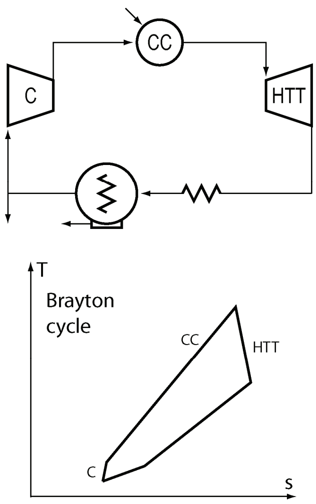

Figure 5. Oxy-combustion Cycle.

The efficiency of the elementary steam cycle can be improved by adding a high pressure and a low pressure turbine, as previously shown in Figure 4 for the advanced STIG cycle. Still, the low pressure turbine also modifies the configuration of the elementary Brayton cycle having the mixture of the above mentioned components A and B as the working fluid. The cycle including these modifications is the Graz cycle (Jericha et al., 2003) (see Figure 6). Note that in Figure 6 the open Brayton cycle having component A as the working fluid is not shown for brevity, and the discussion that follows focuses on the closed Brayton cycle operating with thermal diluents only.

The Graz cycle thermal efficiency (around 64% using syngas as fuel and without taking into account the ASU power) is further improved in the S-Graz cycle (Sanz et al., 2004) (efficiency close to 70%) by increasing the steam fraction in the working fluid (see Figure 7, still shows only the Brayton cycle operating with thermal diluents for brevity). This is possible by compressing the steam in gas form and making it work in the elementary Brayton cycle. This steam substitutes for part of the CO_2 acting as thermal diluent of the combustion. Thus, steam thermal diluent of the combustion compressed in gas form and injected in the combustion chamber is added to the three components (A, B, C) of the Graz working fluid mentioned above.

In order to recirculate the steam in the Brayton cycle the main flow has to be split before entering the LPT (otherwise only water would be obtained after the LPT expansion and condensation). Compared to the Graz-cycle the S-Graz structure is built in order to have all the CO_2 avoid the LPT expansion except the fraction generated as combustion product, which still has to be extracted from the system to satisfy the mass balance in the whole plant. So, as it appears in Figure 7, a simple Brayton cycle with intercooled compression is followed by CO_2 and H_2O, which operates at higher temperature than the B_LP cycle followed by CO_2 only in the Graz-cycle (see Figure 6).

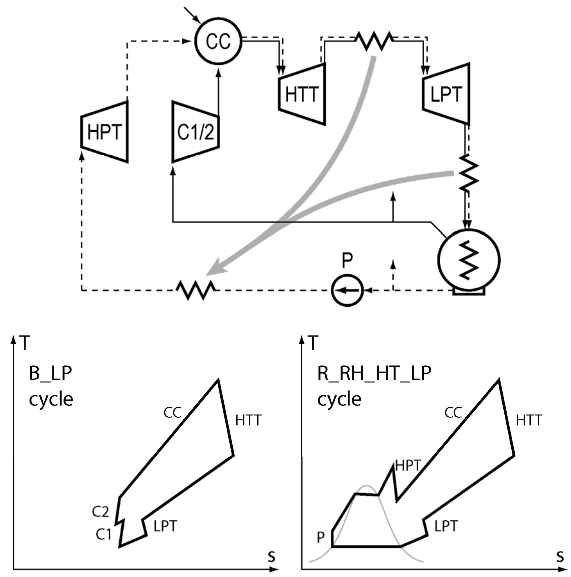

Figure 6. Graz Cycle.

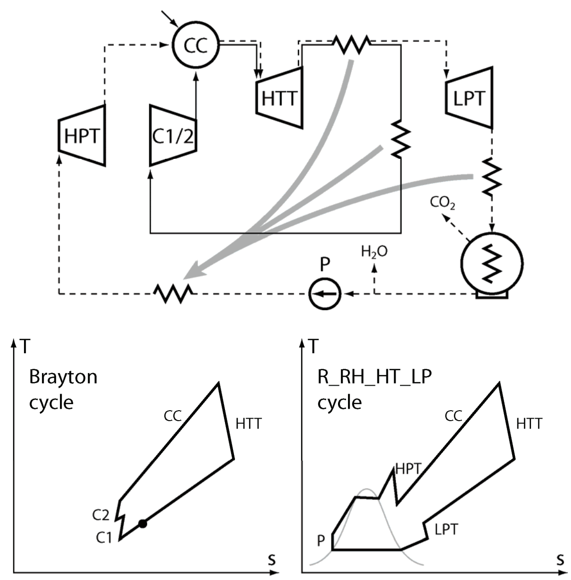

Figure 7. S-Graz cycle.

Accordingly, the average thermodynamic temperature in the heat acquisition phase of this cycle is increased. This is one reason why the thermal efficiency of the S-Graz cycle is higher than that of the Graz cycle, despite the additional compression work. Moreover, the total amount of the heat available at the exit of this elementary Brayton cycle can still be recovered usefully by other internal sinks. Another advantage is that the additional steam allows the condenser pressure to be reduced with a consequent increase of the low pressure turbine power.

On the other hand, technological aspects related to the use of different working fluids in compressors and turbines, which may affect their efficiencies and consequently alter the thermodynamic evaluations, are not considered here.

5. H_2/O_2 Cycles

In Sections 3 and 4 it was shown how the presence of air in evolved STIG cycle configurations and the presence of CO_2 in the S-Graz cycle increases the condenser pressure and decreases the work obtained by the low pressure turbine. So, it appears that having steam as the only working fluid would make it possible to lower the turbine outlet pressure to vacuum as in traditional steam power plants. However, the elementary steam cycle cannot stand "autonomously" because in general it requires heat in the high temperature zone from the internal combustion of a fuel with air or oxygen, as already discussed in Section 3. Nevertheless, if hydrogen is burnt with oxygen, the resulting combustion product is just steam. In order to have only steam as the working fluid, steam has to act as a thermal diluent of combustion as well. A part of this steam is generated through heat recovery, whereas the remaining part is compressed in gas form as already seen for the S-Graz cycle. This is done in the "Topping Extraction Cycle" suggested by Aoki et al. (1998) and Desideri et al. (2001) (see Figure 8). Accordingly, the working fluid is made up of the three following components:

- stoichiometric steam generated by the H_2/O_2 combustion (denoted as A in following sections);
- steam thermal diluent of combustion generated by heat recovery and injected in the combustion chamber (B);
- steam thermal diluent of combustion compressed in gas form up to the maximum pressure of the cycle (C).

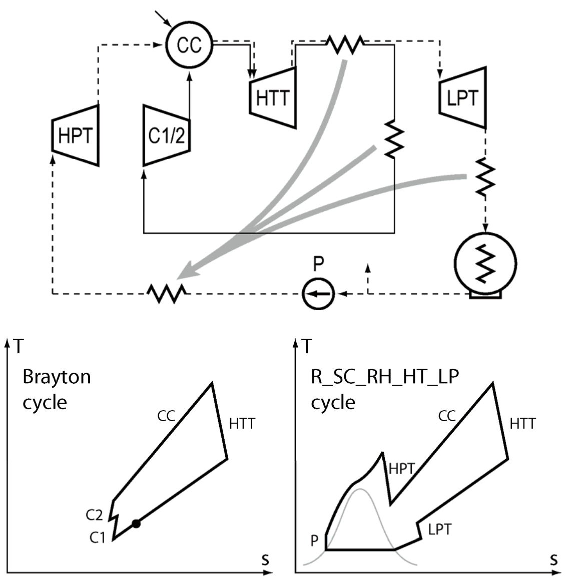

Figure 8. Topping Extraction Cycle (Mitsubishi).

If the efficiency of the elementary Rankine cycle having component B as working fluid were higher than the efficiency of the elementary Brayton cycle having component C as working fluid, it would be convenient to increase the fraction of thermal diluent B and consequently decrease the fraction of thermal diluent C. A higher efficiency for the elementary Rankine cycle can be achieved for instance by increasing the TIT and/or by performing a post-combustion. This leads to a higher temperature of the exhaust gases at the turbine outlet, which allows for an increased temperature at the HPT inlet where supercritical pressures are considered. The latter solution is used in the cycle suggested by Bannister et al. (1999) (see Figure 9) in which the turbine outlet temperature is higher than 1000°C and the only components A and B appear in the working fluid (see also Gambini et al., 2003). So, only one compressor is included in the plant to compress the stoichiometric oxygen up to the maximum cycle pressure. Note that the steam extractions from the LPT for regenerative feedwater preheating are omitted in Figures 8 and 9 for brevity.

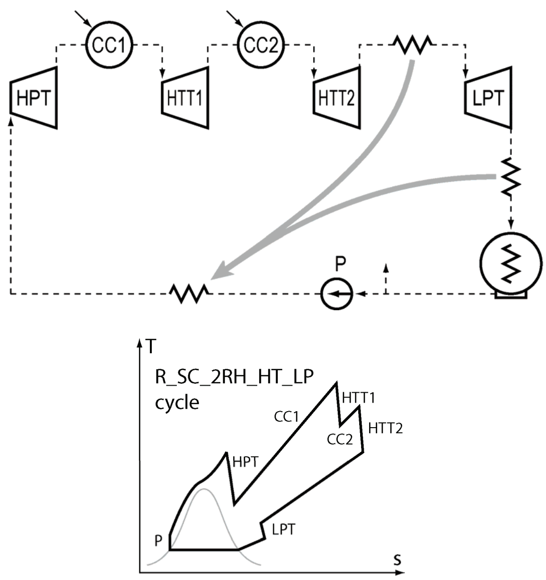

Figure 9. Cycle Proposed by Bannister et al. (1999).

6. Remarks and Conclusions

The example presented in this paper shows that the evolution of a simple Brayton cycle (and in general of any simple thermodynamic cycle) towards more complex and efficient energy systems that can be described in a "user friendly" manner by decomposing the final system configuration into elementary thermodynamic cycles. The criterion is effective and general because it allows one to "reconstruct" the real process followed by system designers in building a complex system configuration, which mainly consists of the two following steps:

i) Finding heat sinks in the basic cycle in order to exploit its available heat sources, and generating consequently an evolved structure of the basic cycle itself;

ii) Adding other sinks and, when necessary, other sources as well, to further improve the system performance/efficiency. This second step may require the addition of new working fluids and, at the same time, new elementary thermodynamic cycles to be partially or totally superimposed on the basic one.

Thus, it immediately appears that following the reverse procedure (separation of the complex structure into elementary cycles), as suggested in this paper, may facilitate the comprehension of the processes involved in different complex system configurations derived from the same basic cycle, and may suggest potential ways for their further improvement.

The application of this criterion makes the comprehension of the various steps in the evolution of a natural gas fuelled Brayton cycle towards more advanced mixed cycles (named here "auto-combined cycles" to highlight the combination of different - gas and steam - cycles within the same system components) easy, and shows similarly the development of a simple oxy-fuelled Brayton cycle with CO_2 capture towards evolved system configurations, such as the Graz and S-Graz cycles and the H_2/O_2 auto-combined cycles.

Acknowledgements

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Nomenclature

P	Pump
C	Compressor
CC	Combustion Chamber
HTT	High Temperature Turbine
HRSG	Heat Recovery Steam Generator
R_HT	Rankine cycle with superheating at high temperature
R_RH_HT	Rankine cycle with reheating at high temperature
STIG	Steam Injected Gas Turbine
HPT	High Pressure steam Turbine
LPT	Low Pressure Turbine
B_LP	Brayton-Joule cycle with the addition of below atmospheric pressure turbine and compressor
R_RH_HT_LP	Rankine cycle with reheating at high temperature and with a low pressure turbine
R_SC_RH_HT_LP	Rankine supercritical cycle with reheating at high temperature and with a low pressure turbine
R_SC_2RH_HT_LP	Rankine supercritical cycle with two reheatings at high temperature and a low pressure turbine

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